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F. E. Lopez, J. E. Hernandez

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# Performance of a Mach-Zehnder based analogue data recording system for use with the Gas Cherenkov Detector on the NIF

A.C. Carpenter<sup>1</sup>, H. W. Herrmann<sup>2</sup>, B. V. Beeman<sup>1</sup>, F. E. Lopez<sup>2</sup>, and J. E. Hernandez<sup>1</sup>

<sup>1</sup>Lawrence Livermore National Laboratory

<sup>2</sup>Los Alamos National Laboratory

## SUMMARY

This paper covers the performance of a high speed analogue data transmission system. This system uses multiple Mach-Zehnder optical modulators to transmit and record fusion burn history data for the Gas Cherenkov Detector (GCD) on the National Ignition Facility. The GCD is designed to measure the burn duration of high energy gamma rays generated by Deuterium-Tritium (DT) interactions in the NIF. The burn duration of DT fusion can be as short as 10ps and the optical photons generated in the gas Cherenkov cell are measured using a vacuum photodiode with a FWHM of ~55ps. A recording system with a 3dB bandwidth of  $\geq 10\text{GHz}$  and a signal to noise ratio of  $\geq 5$  for photodiode output voltage of 50mV is presented. The data transmission system uses two or three Mach-Zehnder modulators and an RF amplifier to transmit data optically. This signal is received and recorded by optical to electrical converts and a high speed digital oscilloscope placed outside of the NIF Target Bay. Electrical performance metrics covered include signal to noise ratio (SNR), signal to peak to peak noise ratio, single shot dynamic range, shot to shot dynamic range, system bandwidth, scattering parameters, are shown. Design considerations such as self-test capabilities, the NIF radiation environment, upgrade compatibility, Mach-Zehnder (MZ) biasing, maintainability, and operating considerations for the use of MZs are covered. This data recording system will be used for the future upgrade of the GCD to be used with a Pulse Dilation PMT, currently under development.

**Keywords:** Mach-Zehnder optical modulator, NIF, GCD

## 1. INTRODUCTION

The National Ignition Facility (NIF) is the largest high energy density science facility in the world and routinely conducts inertial confinement fusion (ICF) experiments. One of the primary methods for determine deuterium-tritium (DT) reaction rates in ICF experiments is by measuring the time history of the MeV gamma rays produced during the implosion [1]. Gas Cherenkov Detectors (GCD) have been used for several years in the OMEGA laser facility at the Laboratory for Laser Energies in Rochester New York [2] [3]. The Gamma Reaction History (GRH) diagnostics fielded at OMEGA and at NIF have also produced high quality reaction history and gamma bang time measurements [4]. The most recent version chamber insertable GCD-3 has improved performance and is planned to be installed on the NIF in the near future. MeV gamma rays Compton scatter electrons from a Beryllium converter foil in a high pressure (~200+psia) CO<sub>2</sub> gas cell. The optical photons generated by the Cherenkov radiation in the gas are collected via mirrors and measured using a vacuum photodiode with a FWHM of ~55ps. A recording system with a 3dB bandwidth of  $\geq 10\text{GHz}$  and a signal to noise ratio of  $\geq 5$  for photodiode output voltage of 50mV is needed to accurately measure the DT reaction history. Current vacuum photodiode technology is the limiting factor in the bandwidth of the system. Future work on a pulse dilation photomultiplier tube is expected to have a photocathode response 20 times the temporal response of the fastest photomultiplier tubes (PMTs) currently available with the same output bandwidth.

The NIF implementation of the GCD diagnostic will primarily locate the Gas cell in in an existing chamber re-entrant well [5]. This well has an insertable cradle that can be retracted for installation of the GCD then allows the cell to be inserted to an operating distance of about 4m. For some experiments the Gas cell must be installed in a Diagnostic Instrument Manipulator (DIM) and inserted much closer to Target Chamber Center (TCC). The recording system discussed in this paper only covers the use of the GCD in the 3.9m re-entrant well.

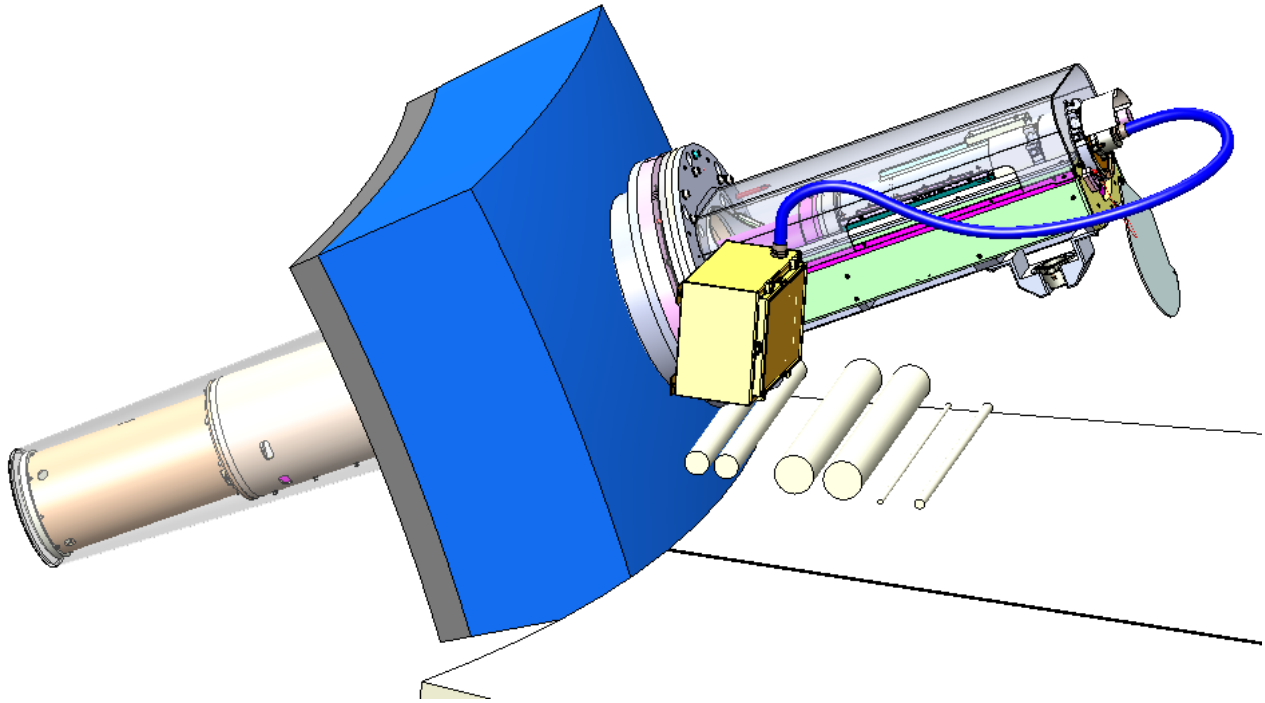


Figure 1. NIF Target Bay components for the GCD system, Junction box, GCD Gas Cell, and Insertion Hardware.

## 2. REQUIREMENTS

### 2.1 GCD System Engineering Analysis

A systems engineering analysis of the diagnostic was performed and key expectations for the system were derived. The objective was to install the GCD3 diagnostic in the existing nTOF-3.9m diagnostic well and record temporally resolved background data and  $^{12}\text{C}\gamma$  data resolution on shots with total neutron yields equal to or greater than  $1\text{e}15$ . The key expectations are listed below.

- Use this platform to understand background sources in the GCD and develop a shielding plan for the “superGCD”
- Record gamma reaction history data with improved sensitivity and time resolution (improved with respect to the existing GRH diagnostic)
- Have sufficient recording bandwidth to support measurements using a Photek photodiode
- Install this in the existing nTOF-DSF well while meeting expectation from LANL for fielding the GCD3
- Operate and install this system safely and with minimal impact to shot operations

The recording system had a goal of reusing as much of the infrastructure from the nTOF-DSF-MZ system, while maximizing the system bandwidth for the signals of interest.

The recording system was required to interface with a Photek PD010 photodiode or PMT110 photomultiplier tube with a standard female SMA output. The bandwidth for the PD010 is about 8GHz. The photodiode is biased with up to -5kV and the output signal is proportional to the intensity of Cherenkov light generated in the gas cell.

### 2.2 Performance Requirement Basis

The first step in analyzing the performance required for the recording system was to determine the bandwidth of the input signal. Simulations of the dispersion of the optical signal generated in the gas cell limit the system’s optical

response to a rise time of about 10ps. The data sheet provided by the diode manufacturer (Photek) stated the rise time of the PD010 to be about 50ps. The impulse response of each photodiode is unique requiring that it be measured.

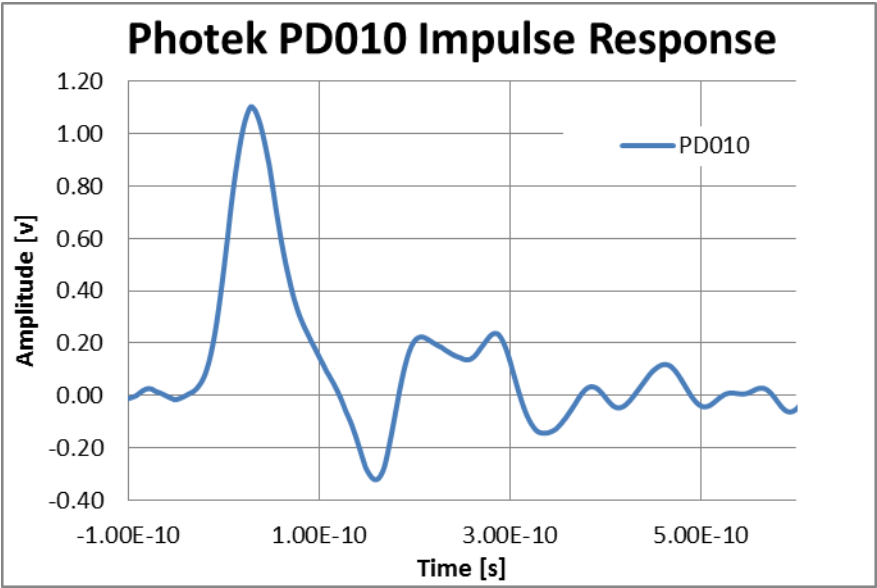


Figure 2. Photek PD010 Impulse Response Function (IRF)

The impulse response function for the Photek PD010 photodiode was measured using a 2ps 400nm laser in the Short Pulse Lab at NSTec Livermore. The response shown in Figure 2 was recorded on a 16GHz oscilloscope with a high bandwidth attenuator and 3 foot high bandwidth cable. The PD010 rise time (rt) is estimated to be about 40ps. Taking into account the bandwidth of the scope and the cable we can estimate the rt to be about 36ps. In a similar way we can estimate the full width at half max (FWHM) is about 60ps or about 55ps when the oscilloscope and cable are accounted for. Based on the relationship of a Gaussian systems rise time to bandwidth  $\approx 0.35/\text{rt}$  ( $0.34/36\text{ps}\approx 9.4\text{GHz}$ ) or using the similar FWHM relationship  $\text{bandwidth} \approx 0.44/\text{FWHM} \approx (0.44/55\text{ps}\approx 8\text{GHz})$  the approximate bandwidth of the photodiode is 8-9GHz. The IRF of the photodiode is not Gaussian however the general approximate can be used to estimate the needed bandwidth of the recording system; in this case the bandwidth of the recording system should be  $>10\text{GHz}$ . Due to design compromises and budget limitations the limiting component in the recording system was the oscilloscope at 12.5GHz.

Based on data taken with the GRH diagnostic at 6m from target chamber center (TCC) the expected output voltage from a unity gain PD010 for a shot with  $1\text{e}15$  neutron yield was 50mV with output voltage scaling linearly with neutron yield. From the system engineering analysis this was determined to be the minimum signal of interest for the GCD diagnostic and the minimum SNR for this signal was determined to be 5. For shots with yields less than  $1\text{e}15$  a PMT with adjustable gain and reduced bandwidth would be used. The maximum expected signal using a PD is 500mV based on a total neutron yield of  $1\text{e}16$ . These values maximum and minimum output voltages result in a single shot dynamic range requirement of 10:1.

2.3 Requirements Summary

The key electrical recording system requirements are listed in Table 1. The preliminary acceptance test plan results showed that all requirements were met.

Requirement Category	Required Value	ATP Test Result
Single Shot Input Range	50mV to 500mV	45mV to 700mV

Single Shot Dynamics Range	$\geq 10$	>14 (for min input)
Minimum SNR for	$\geq 5$	$\geq 5$ for signals $\geq 45\text{mV}$
Recording System Bandwidth	$\geq 7\text{GHz}$ amplified, Limited by scope BW	$\geq 10\text{GHz}$ unamplified $\geq 8\text{GHz}$ amplified

Table 1. Electrical Requirements and ATP results

### 3. DESIGN

#### 3.1 Design Philosophy

The recording system design philosophy focused on meeting the Signal to Noise Ratio (SNR), bandwidth, and dynamic range requirements while reusing as much of the existing nTOF-DSF-MZ recording system infrastructure as possible. The approach focused on determine what the actual photodiode performance was then designing the recording system to transmit and record signals from this source with minim loss of bandwidth and sufficient fidelity. Prototyping and offline testing were favored above simulation due to the available resources and scope of the project. Simple SNR, sensitivity, and dynamic range calculations were performed then bench testing confirmed system level performance.

Lesson Learned from the multiple Mach-Zehnder (MZ) based diagnostics on the NIF including, GRH, nTOF-BT, nTOF-DSF-MZ, SPBT-MZ, and design studies on a MZ based Dante upgrade were included in the design phase [6] [7]. The GCD system uses a low noise high output (100mW) drive laser to reduce the noise floor. Photorecievers from New Focus were upgraded with internal heat sinks and automatically powered down between shots to prevent failures seen with previous 1544-B models seen in other diagnostics. Improved access to the MZ hardware in the target bay was also a priority to allow for repairs and future upgrades. Additional design improvements including a more advanced ramp based bias controller and replacing the polarization maintaining optical fibers with polarizing fibers were not performed due to the cost and complexity that would have been added to the design.

#### 3.2 Mach-Zehnder Response Sensitivity and Signal to Noise Ratio

One approach to operating a MZ based analog communication link is to bias the MZ at its most sensitive bias point known as quadrature typically referred to as Q+ or Q- [8]. This produces the maximum light modulation for a given voltage input. The voltage required for a MZ modulator to modulate the light output by 180 degrees is known as  $V\pi$ . The output signal sensitivity or input change divided by output response is reduced as the output moves towards the maximum or minimum transmission condition typically referred to as max or min. If the phase of the modulate is set via an external bias controller to Q+ for the sensitivity and the input signal is set to 0V the sensitivity will drop be reduced to a minimum when the input signal has increased to  $V\pi/2$ . Typically re-construction of the original input signal is accomplished by first taking the arcsine of the output and then deconvolving the response of the MZ. When MZs are used in a stacked configuration a second less sensitivity channel is designed to take over when the first channel's sensitivity is reduced beyond an acceptable level. A general rule of thumb for a single channel of a high bandwidth MZ system has been to keep input signals below  $V\pi/6$  if possible (14% reduction in sensitivity) and a firm limit  $V\pi/4$  (29% reduction in sensitivity) before the next channel should be used. Figure 4 shows the reduction in sensitivity as a function of input  $V\pi$ .

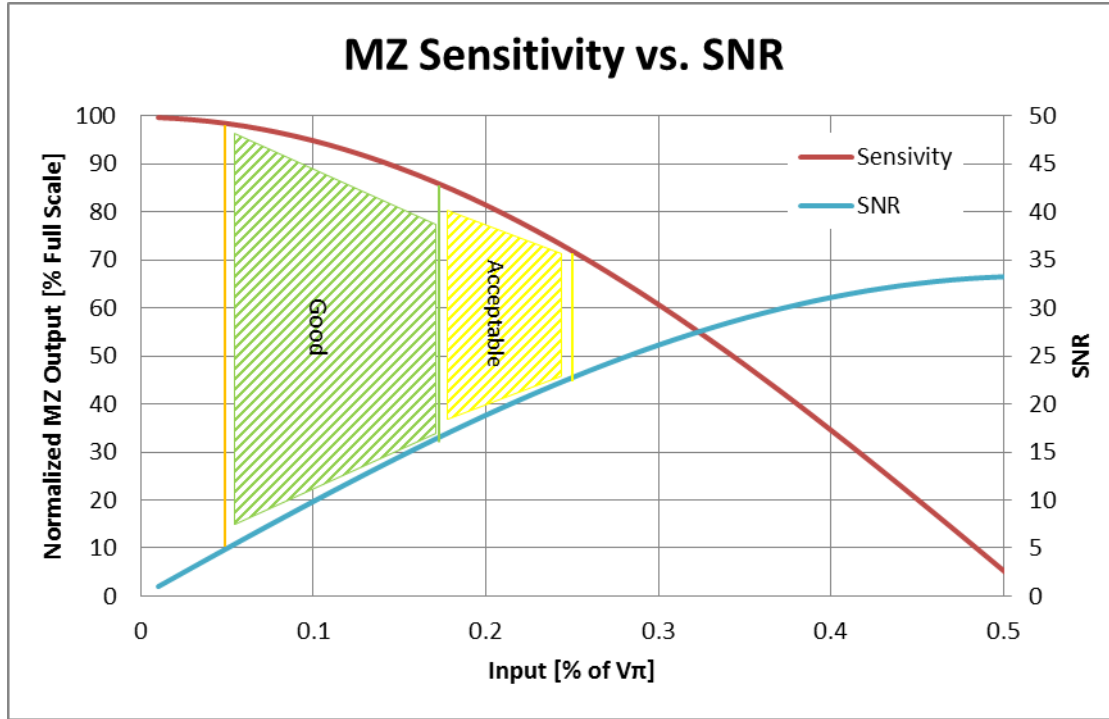


Figure 3 Mach-Zehnder (MZ) Sensitivity and SNR plotted together. MZ Sensitivity is defined as output as a percentage of input on the left axis and peak signal SNR for a fixed RMS noise floor is plotted on the right axis.

The recording system noise floor for this MZ recording system is determined by the quadrature sum of the components in the system. The RMS noise floor for the recording system was  $\sim 12\text{mV}$  with dominant noise source coming from the oscilloscope. Figure 3 shows the SNR for inputs as a function of the effective  $V\pi$  for the input after taking into account the splitters and amplifiers in the system. This shows that to achieve a  $\text{SNR} > 5$  the minimum input signal must be about  $V\pi/20$ .

Together the minimum SNR and the reduction in sensitivity limit the useful range for a single MZ channel; therefore the input signal is split unevenly over multiple channels to increase the single shot dynamic range. The process of splitting and then stitching MZ signals back together is often referred to as stacking.

### 3.3 Hardware Design and Component Selection

Rack hardware including the oscilloscope and photoreceivers were upgraded to improve bandwidth and lower the noise. It was determined that the telecommunication 1550nm MZ drive laser from EM4 and the bias controllers would have sufficient performance to meet the needs of the design, this also minimized the need for new hardware. All of the original nTOF-DSF-MZ hardware was removed and a new junction box with the all of the recording system components was designed and installed in the TB. This junction box interfaces with the GCD via a EMI conduit and a Times Microwave HF-290 high bandwidth coaxial cable. The conduit also provides space the high voltage bias needed to operate the photodiode.

Target Bay junction box hardware includes, upgraded MZs from Covega, Teledyne Coax Switch (CCR-33K), Tektronix power dividers (PSPL5372) and Tektronix amplifiers (PSPL5840B). All additional jumper cables, adapters, and DC-Blocks had a minimum bandwidth of 18GHz. The high bandwidth requirements of the GCD system lead an architecture where several MZs are “stacked” such that when the sensitivity of one MZ was reduced below an acceptable level the signal on the next less sensitive MZ would be used. The system input signal can be reconstructed by stitching multiple channels together after unfolding and then deconvolution each channel separately. Typically commercial MZ are built with a Lithium Niobate ( $\text{LiNbO}_3$ ) crystal and have a RF  $V\pi$  between 3 and 8 volts. A smaller  $V\pi$  will result in a lower

voltage needed to modulate the light. The MZs used in the original system did not have sufficient bandwidth and the  $V_{\pi}$  was too large to work in the new system. Low  $V_{\pi}$  MZs (Mach-LN-058) from Covega were chosen for their ~20GHz bandwidth and 2.3V. A summary table of the key components in the GCD system is listed in Table 2.

Component	Bandwidth	Comment
Scope (Tektronix DPO71254C)	12GHz	Limiting BW component
Photoreciever (New Focus 1474-A)	38GHz	Low noise and high bandwidth
Amplifier (Tektronix PSPL5840B)	13.5GHz	Needed for signals below 150mV
MZs (Covega LN 058: Low $V_{\pi}$ )	20GHz	Very low RF $V_{\pi} \approx 2.1V@1GHz$
Teledyne Coax Switch (CCR-33K)	33GHz	Allows test pulses to be switched in
Tektronix Power Divider (PSPL5372)	26GHz	80/20 split ratio
Times Microwave Cable (HF290)	18GHz	Maximum cable length 10 feet

Table 2. Key components in signal path for GCD MZ recording system

### 3.4 System Level Design

A simplified system block diagram is shown for the primary configuration in Figure 4. All active components with the exception of the vacuum photodiode, MZs, and the RF amplifier are installed outside of the TB to shield them from the NIF radiation environment. Fibers, coaxial cables, and twisted pair copper cables are used to control, bias, and transmit all of the data between the Diagnostic Mezzanine and the GCD gas cell.

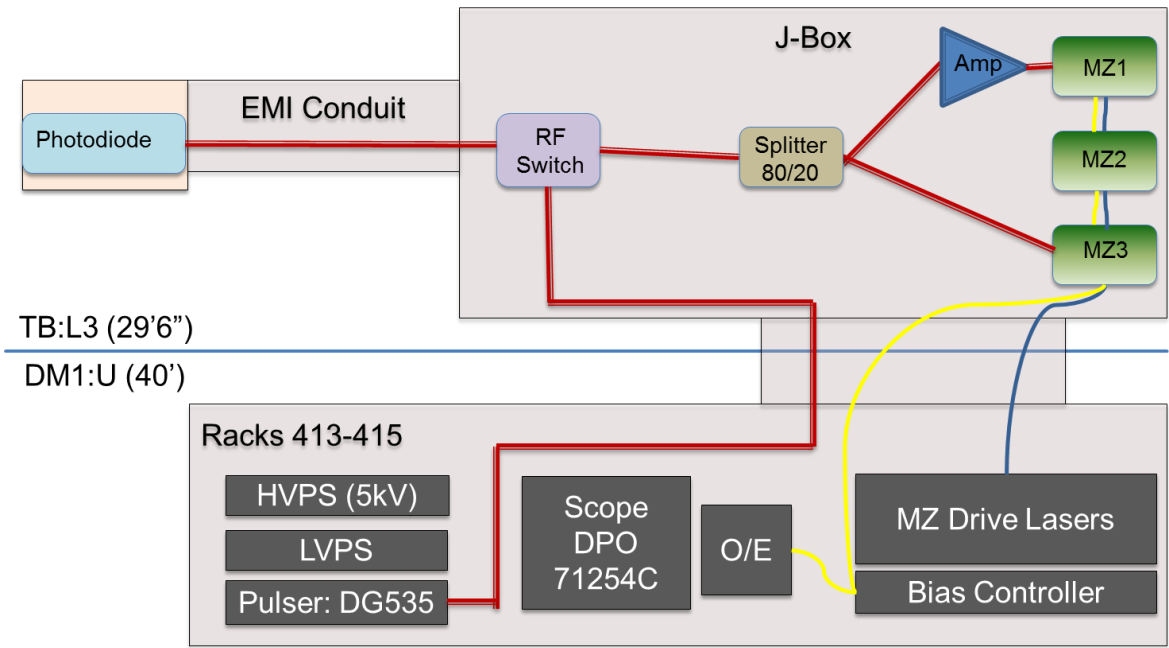


Figure 4. System Block Diagram



### 3.5 Operational Modes

From the chart and discussion in section 3.2 it is clear that the dynamic range and SNR requirements cannot be achieved with a single MZ. If the input signal is split unevenly via a match 80/20 power divider and the 20% output is amplified by a 21dB a minimum SNR of 5 for 50mV signals using a MZ with an RF  $V\pi$  of 2.3 can be achieved. If the 80% output of the power divider is sent directly into a second MZ with a similar RF  $V\pi$  the dynamic range can be extended to accept inputs up to 700mV without exceeding  $V\pi/4$ . This configuration is shown in Figure 5 and is referred to as option1. Although only two MZs are needed to meet all of the systems requirements the original nTOF-DSF-MZ system had provisions for 3 MZ. To accommodate future needs of the system the a 3<sup>rd</sup> MZ data channel was installed but is not used at this time. A feature of the Tektronix DPO71254C oscilloscope is the ability to increase the sample rate for two channels to 100GS/s if only two channels are used. To take advantage of this feature oscilloscope channels 1 and 3 are used while channels 2 and 4 must be left off. A 1 $\omega$  (1053nm) timing fiducial is optically combined at the input to the photorecievers with the 1550nm modulated light from the MZs.

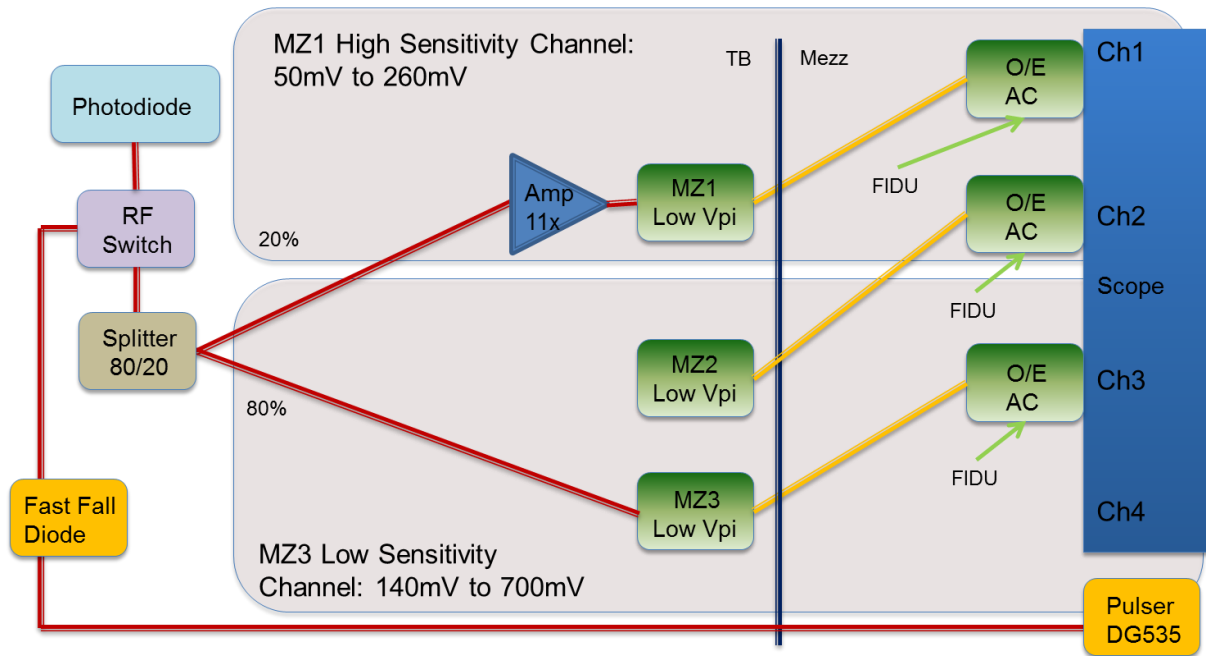


Figure 5. Simplified Electrical Configuration for Option1

#### 3.5.1 Electrical Configuration Option 1

Option 1 achieves a MZ split ratio of 2.75:1 by amplifying 11x the 20% leg of an 80/20 power divider. Option 1 is shown in figure 5. The minimum input signal is approximately 50mV for a SNR of 5. Selection of the Photorecievers and MZ drive lasers with very low noise results in the dominate noise source being the oscilloscope. Generally, scope noise is proportional to the full scale voltage range so optimizing the photoreciever gain and drive laser output results in best performance when the scope is set in the range of 200 to 300mV full scale. The single shot dynamic range of this system 14:1. This will be the primary configuration used with the photodiode. The bandwidth of the RF amplifier limits the most sensitive channel. Increase performance could be achieved with a lower gain higher bandwidth amplifier at the expense of dynamic range or sensitivity.

#### 3.5.2 Electrical Configuration Option 2 and Additional Configurations

A second option is achieved by bypassing the amplifier and sending 20% of the signal directly into MZ1. In this case the split ratio is 4:1. The minimum input signal is about 140mV depending on the vertical scale used and the single shot dynamic range is increased to 20:1. The addition of a second splitter that utilizes the third MZ can further increase dynamic range up to 100:1. Moreover, the addition of additional amplifiers or attenuators can be used to optimize the out split ratios for future applications. It is not recommended to exceed a split ratio of 5:1 due to the drop off in sensitivity and poor overlap of MZs with sufficient SNR.

### 3.5.3 Self-Test Capability

To improve reliability of the system a self-test pulse feature was included in the design. Using the output of a digital delay generator (Model: DG535) and a fast fall step recovery diode a relatively short pulse can be switched into the input to the system. This feature is shown in figure 4, the system block diagram. A voltage applied to the electro mechanical RF switch will allow a test pulse generated in the mezzanine to be sent through the system. The DG535 output pulse should have an amplitude  $> V\pi/2$  to verify that the MZ is biased properly at quadrature (Q+/Q-). The maximum safe input amplitude for the RF amplifier will be exceeded before MZ3 had reached  $V\pi/2$ . MZ1 is tested in a first dry-run with a safe input for the amplifier, then the amplifier is powered off and a larger test pulse is sent into the system to test the bias of MZ3.

### 3.6 Design Considerations

The GCD recording system can easily be re-configured and serviced as needed. All of the TB hardware is installed on a removable plate and access to the amplifier, MZs, and power dividers can be done by simply removed the junction box door. Figure 6 shows the junction box with the door removed. A requirement of the GCD recording system was the ability to accommodate PMTs with high output signals and the future use of a pulse dilatation PMT in phase 2 of the GCD diagnostic plan. The discussion in section 3.5.2 covers the possible electrical configurations that will be implemented in the future or if using a PMT.

The GCD gas cell and MZ recording system must operate in the radiation environment of the NIF TB. The MZ recording system junction box was located out of the port line of sight behind the target chamber wall and gunite. This reduces the high energy neutron flux by about an order of magnitude, when compared placing the system behind the GCD gas cell. Additionally, the MZs are surrounded by 10mm of tungsten shielding to reduce the impact of X-rays. The GCD is designed to primarily operate a yields  $>1e15$ . The use of active non-radiation hardened electronics in the neutron environment presents a risk, however for yields  $>3e15$  it is expected that there will sufficient signal to collect data on the channel that does not utilize an RF amplifier. When the total neutron yield is  $\leq 3e15$  the prompt neutron flux on the amplifier will be  $< 1e9n/cm^2$ . This flux is not expected to cause failures of the analogue electronics. Before and after every the self-test dry-runs will be conducted to verify that the performance of the amplifier has not been impacted.

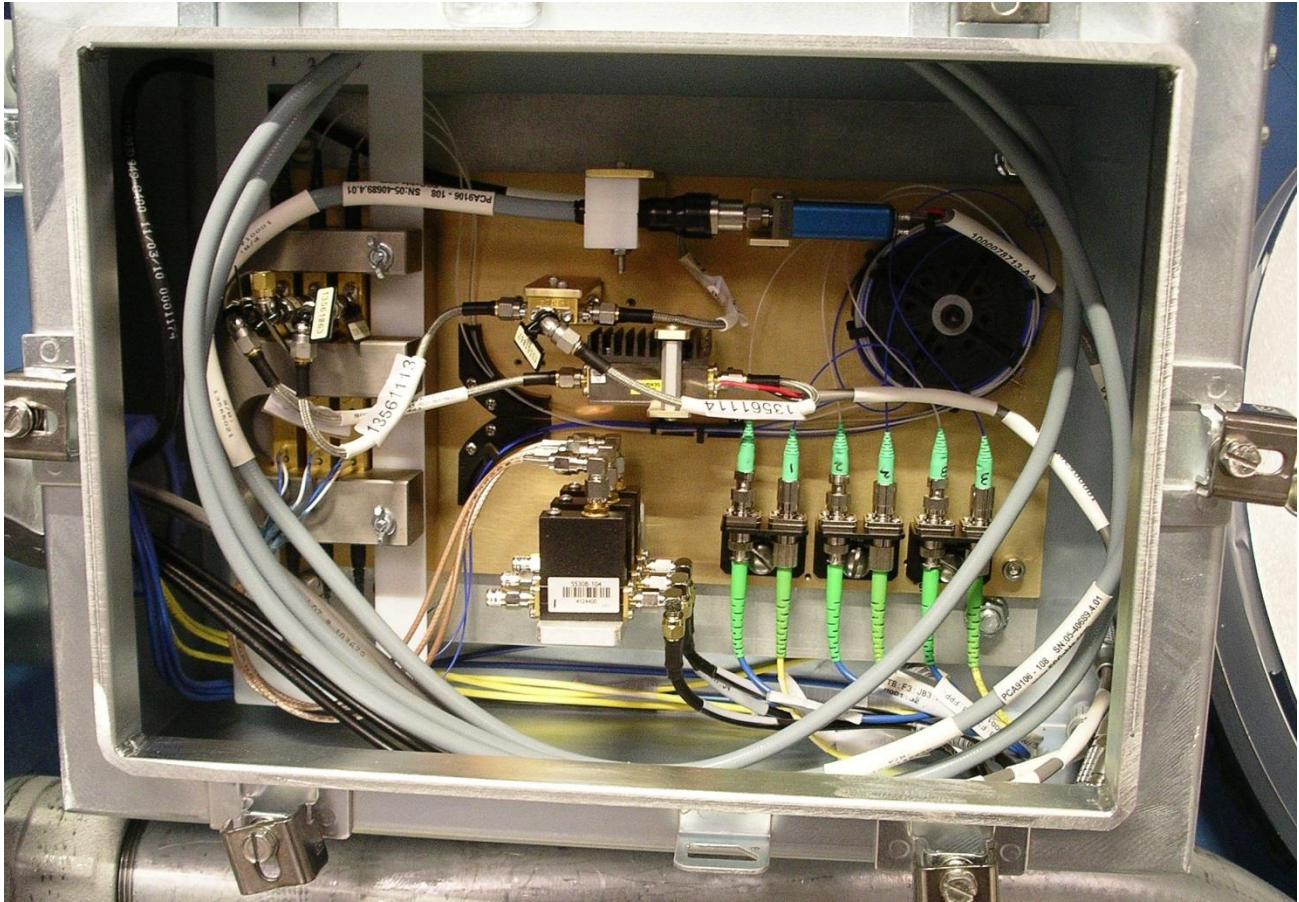


Figure 6. GCD Junction Box installed in the NIF TB

The high speed output of the Newport 1474-A photorecievers is AC coupled. The light level sent to the photorecievers through MZ when biased at quadrature must be known for proper signal reconstruction. The photorecievers have a separate low bandwidth DC coupled monitor that is recorded on a low speed National Instruments compact field point based digitizer. There is no lower bandwidth limit requirement for the GCD due to the fact that the signals of interest have very little low frequency content. Additionally, all signal inputs to the system must be AC coupled. The DC bias required for MZ operation is, internal to the MZ module, electrically connected to the high speed RF 2.92mm input connector. DC blocks are placed between the inputs to MZs and after the fast fall test pulse diode.

#### 4. SYSTEM TESTING AND PERFORMANCE

One of the major objectives of this work was to verify, before installation, that all performance requirements could be met. Testing was completed in several phases starting with preliminary component level test to evaluate different options. The choice of Photoreciever and MZ were results of this preliminary process. Past testing of MZ systems has shown that using a short pulse alone to determine the system's transfer function can prove difficult due to the noise and lack of low frequency content. Improved results have been obtained using step responses. Additionally, direct measurement of the scattering parameters could be achieved because the input and output where physically located in close proximity during bench testing.

##### 4.1 Test Methodology

The complete system was tested with a short pulse, steps, and a vector network analyzer (VNA). The system was prototyped using all components to be installed in the NIF with the exception of the 150' fiber optic cables. System bench testing included the use of a 9-foot input cable and photorecievers connected directly to the oscilloscope with no

jumper cables. The objective was to obtain transfer functions for the various system configurations using multiple methods as well as verify the SNR, sensitivity, and determine any unexpected operating limitations.

## 4.2 System Pulse Testing

Pulse testing with an impulse forming network PSPL5210 connected to the output of a Picosecond Pulse labs Model 4005, 11ps fall time calibration source was used to mimic the photodiode output. The FWHM of the test pulse was measured to be about 63ps on our 12.5GHz scope. This pulse is very similar to the IRF of the photodiode. Plots in Figure 7 (left) show the input and output for the two data channels used in option 1. For channel 1 a 45mV pulse was sent to the input of the system and a 20mV signal was recorded. The FWHM of this signal was 74ps and the SNR was about 10. Because all signals are recorded as single shot events the signal to peak to peak noise is also an important metric. In the case of channel 1 the  $SNR_{pk-pk}$  was about 3.3. Figure 7 (right) shows the response to a 245mV input on the unamplified channel 3. The FWHM is observed to be about 65ps and SNR is  $SNR_{pk-pk}$  was greater than 5. These plots show that the system exceeds the minimum SNR requirements. It is noted that the noise floor was lower than expected largely due to the low noise diode lasers and the photorecievers.

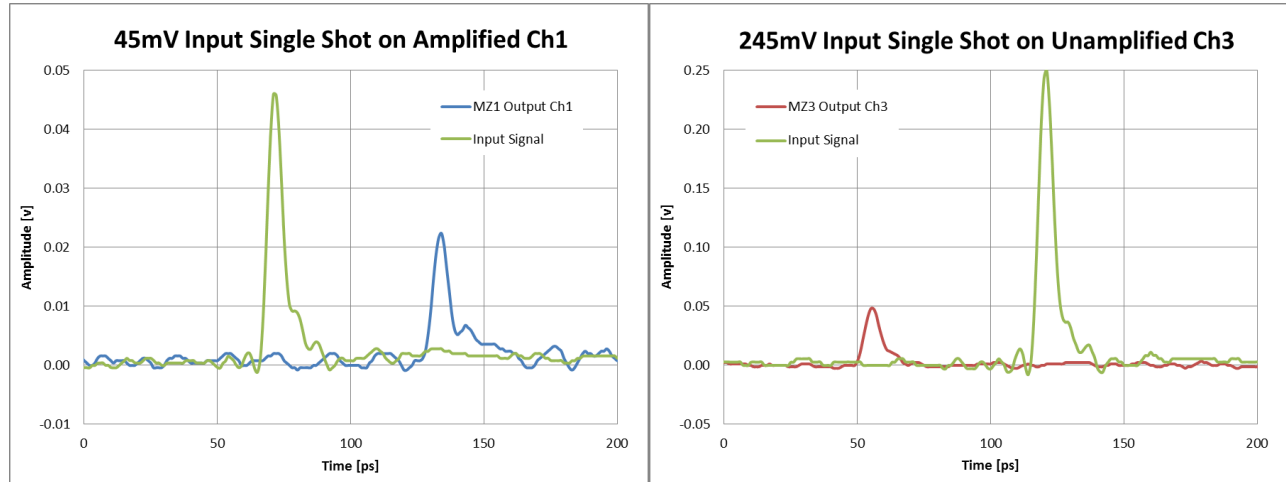


Figure 7. Short pulse response from amplified (left) and unamplified (right) channels configured as option 1.

## 4.3 Scattering parameters and Frequency Response

Direct measurement of the scattering parameters was taken using a 20GHz Vector Network Analyzer (VNA). Although, the system does have a non-linear sinusoidal response, for sufficiently small signals the output can be assumed to be linear with respect to the input, see section 3.2. The system can be viewed as a 3-port electrical network with the input cable defined as port 1 and ports 2 and 3 defined as the outputs of photorecievers. S21 and S31 for options 1 and 2 are shown in figure 8. The system has gain and therefor the absolute power values will change with the DC light level sent to the Photoreciever. Most MZs exhibit large variation in their response at low frequencies and for the purposes this application low frequency content can be ignored. If a lower bandwidth requirement of 1GHz is chosen an average reduction of 3dB is observed at >10GHz for the outputs. A characteristic of the Covega MZs is the relatively slow roll off in the frequency response, meaning that even high frequency content can be recovered if a sufficient transfer function is generated. S31 is very similar for option 1 and option 1, as expected.

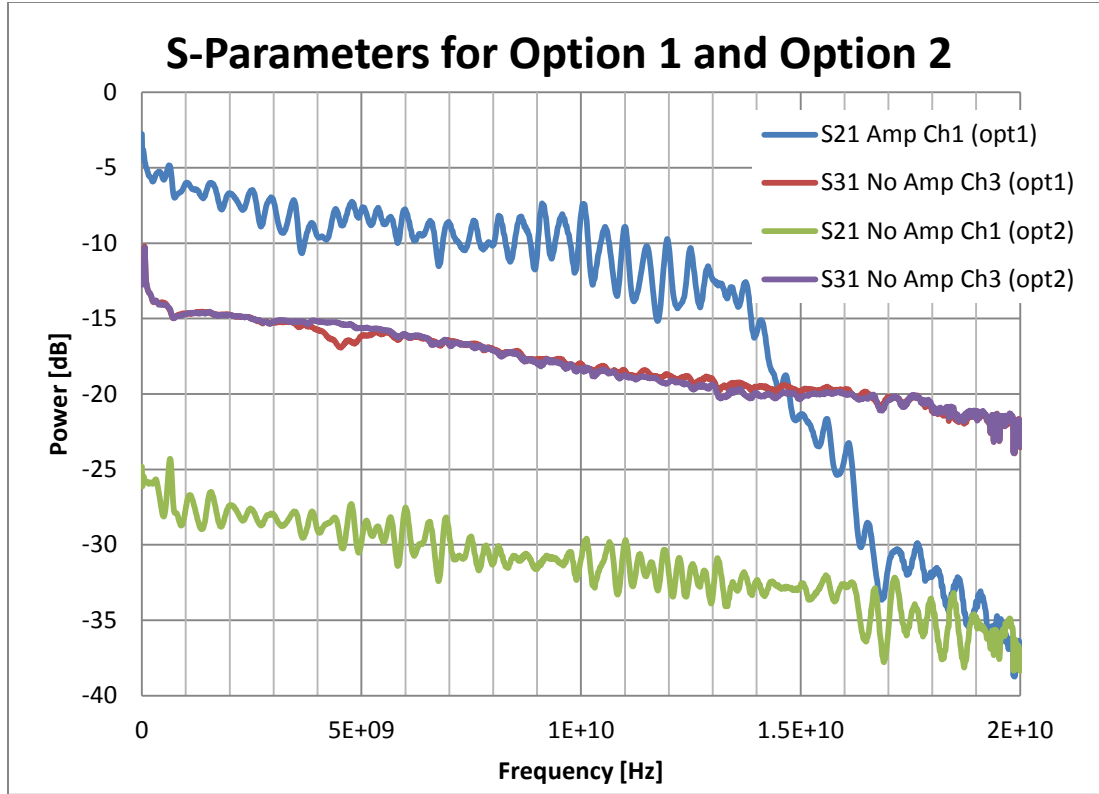


Figure 8. Forward Scattering Parameters for Option 1 and Option 2

S21 from channel one shows oscillations with and without the amplifier. It is assumed that this oscillation is due to reflections in the power divider network MZ network that may be generating standing waves, however further investigation is needed to verify that this is the source. Oscillations were not observed in individual S21 measurement for each MZ.

## 5. CONCLUSIONS

The design presented shows that the GCD recording system will meet or exceed the phase 1 requirements determined in the systems engineering analysis. A SNR > 5 for signals > 50mV can be recorded with a bandwidth > 8GHz while achieving a single shot dynamic range of 14:1. The recording system has been installed in the NIF Target Bay and pulse tested to verify that it is ready for use with the GCD gas cell and photodiode. Phase 2 of the GCD diagnostic system will replace the PD with a pulse dilatation PMT. This new PD-PMT will shorten the rise time of the PMT by a factor of 10 while reducing the output bandwidth by half when compared to the PD010 vacuum photodiodes discussed in section 2.2. The current recording system is designed to accommodate this upgraded. The high speed analogue data transmission system described and analyzed in this paper can be repackaged for used in any application where high bandwidth measurements of small signals in harsh environments are needed.

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